INVESTIGATIONS ON IN-PLANE LOADED WOODEN ELEMENTS – INFLUENCE OF LOADING AND BOUNDARY CONDITIONS

UNTERSUCHUNGEN AN SCHEIBENBEANSPRUCHTEN HOLZ-WANDELEMENTEN – EINFLUSS DER BELASTUNG UND DER LAGERUNGSBEDINGUNGEN

ETUDE DES MURS EN BOIS CHARGES DANS LEUR PLAN – INFLUENCE DU CHARGEMENT ET DES CONDITIONS D'APPUI

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SUMMARY

Investigations on in-plane loaded wooden wall elements are part of a comprehensive research program performed in recent years at University of Ljubljana to enable better understanding of response of wooden buildings exposed to earthquake action. Recently, Division of Timber Construction of MPA University of Stuttgart joined the research program. This paper reports on some results emerging from the research cooperation.

Eurocode 5 contains two methods for determination of the racking strength of cantilever-type wall diaphragms: an analytical approach and an experimental approach using the test protocol according to EN 594. Both approaches are related only to timber frame walls having sheathing plates. The test procedure according to EN 594 predefines the partially anchored wall which does not necessarily represent the actual anchorage and loading conditions in the building and does not apply for cyclic horizontal loads to simulate earthquake loadings. It is reported on experimentally obtained responses of wall elements with different build-ups exposed both to the EN 594 protocol and to cycling loading. In detail three different cases of boundary conditions that may occur in real structures and the influence of additional vertical loads is regarded.

ZUSAMMENFASSUNG

Untersuchungen zum Tragverhalten von in Scheibenebene beanspruchten Wandelementen aus Holz und Holzwerkstoffen sind Teil eines umfassenden Forschungsprogrammes, das in den letzten Jahren an der Universität von Ljubljana durchgeführt wurde. Das Ziel des Vorhabens besteht in dem besseren Verständnis von Holztragwerken unter Erdbebeneinwirkung. Die Abteilung Holzbau der MPA Universität Stuttgart nimmt seit einiger Zeit im Rahmen einer Kooperation an diesem Forschungsprogramm teil. Der vorliegende Aufsatz berichtet über einige Ergebnisse der gemeinsamen Forschungsarbeiten.

Eurocode 5 beinhaltet zwei Ansätze zur Bestimmung der Schubtragfähigkeit kragarmähnlicher Wandscheiben: einen analytischen Ansatz und eine experimentelle Methode mit einem Belastungsprotokoll nach EN 594. Beide Ansätze beziehen sich ausschließlich auf beplankte Holztafelelemente. Das Prüfverfahren nach EN 594 definiert eine partiell verankerte Wandtafel, die im allgemeinen nur bedingt die tatsächliche Wandscheiben-Verankerung und Belastung des Gebäudes repräsentiert. Das Belastungsprotokoll läßt sich nicht auf zyklische horizontale Lasten zur Simulation von Erdbebeneinwirkungen anwenden. In dem Aufsatz wird über das Tragverhalten von Wandelementen unterschiedlichen Aufbaus berichtet, die gemäß EN 594 und mittels zyklischer Beanspruchung belastet wurden. Im speziellen wird der Einfluß von drei unterschiedlichen Lagerungsrandbedingungen, die in einem realen Bauwerk auftreten können und der Einfluß Höhe der zusätzlichen vertikalen Auflast untersucht.

RESUME

L'étude du comportement des murs en bois ou matériaux dérivés chargés dans leur plan fait partie d'un large projet de recherche réalisé à l'université de Ljubljana ces dernières années. Le but de ce projet est de mieux comprendre le comportement des constructions en bois soumises à des charges sismiques. Le département bois de la MPA de l'université de Stuttgart participe à ce projet depuis quelque temps dans le cadre d'une coopération. Cet article rend compte des premiers résultats des travaux de recherche communs.

L'Eurocode 5 contient deux approches pour déterminer la capacité portante en cisaillement des murs en porte-à-faux: une approche analytique et une méthode expérimentale utilisant le protocole de chargement selon EN 594. Ces deux méthodes sont limitées à l'application aux murs à ossature avec des panneaux latéraux. La méthode expérimentale selon EN 594 définit un ancrage partiel des murs, ce qui ne représente pas nécessairement l'ancrage réel des murs et la sollicitation du bâtiment. Le protocole ne peut pas être appliqué à des charges horizontales cycliques simulant l'action de séismes. Cet article rend compte du comportement de murs de différentes configurations sollicités selon EN 594 et par un chargement cyclique. En détail, l'influence de trois différentes conditions d'appui pouvant apparaître dans un bâtiment et des charges verticales supplémentaires est analysé.

KEYWORDS: Wall elements, diaphragms, racking strength, boundary conditions, loading protocols, cyclic loading, element responses

1. INTRODUCTION

The post earthquake observations of damaged wooden houses and analysis of experimentally tested structural elements developed the world wide knowledge about response of wooden buildings on earthquake and strong wind. One of the major problems of understanding is related to boundary conditions and influence of vertical loading on building elements. Learning from experimental and on-site observations researchers have developed different test protocols and test set-ups aiming at a simulation of the natural behaviour of buildings as realistic as possible. Some of those efforts are reflected in codes and standards.

Eurocode 5 introduces two methods for determination of the racking strength of cantilever-type wall diaphragms: i) an analytical approach and ii) an experimental approach using a test protocol according to EN 594. Both approaches are related exclusively to timber frame walls with sheathing plates. However, the current construction practice introduces many other types of wooden wall diaphragms. Amongst them, increasingly very popular are multi-layer board or perforated glued elements and braced walls with different diagonal strengthening.

The Eurocode 5 calculation procedure is based on the lower value of the plastic capacity of the fasteners which connect the sheathing plates to the timber frame. The approach however is exclusively applicable to the assessment of the racking strength of elements having wood based sheathing plates and frame studs which are fully restrained. In the cases of partially anchored studs and low magnitudes of vertical loading, the calculation may result in load capacity estimates that significantly overestimate the time load-bearing capacity [DUJIC

2001] and [DUJIC AND ZARNIC 2002]. The test procedure according to EN 594 requests a partially anchored wall that does not necessarily represent the actual wall diaphragm used for the construction of the wooden buildings. Further, the EN 594 load protocol does not use a cyclic horizontal load to simulate earthquake loading. It is obvious from the above, that both, analytical and experimental methods addressed in Eurocode 5 need to be upgraded.

In this paper experimentally obtained responses of wall elements exposed both to the EN 594 protocol and to cycling loading are presented. Three different cases of boundary conditions that may occur in real structures were applied and the magnitude of the constant vertical load was varied.

2. THE TEST APPROACH

2.1 Boundary conditions of shear wall elements

Basically, three major cases of boundary conditions are most likely to appear in reality:

- **shear cantilever mechanism**, where one edge of the panel is supported by the firm base while the other can freely translate and rotate ("Case A", Fig. 1)
- **restricted rocking mechanism,** where one edge of the panel is supported by the firm base while the other can translate and rotate as much as allowed by the ballast that can translate only vertically without rotation ("Case B", Fig. 1)
- **shear wall mechanism,** where one edge of the panel is supported by the firm base while the other can translate only in parallel with the lower edge and rotation is fully constrained ("Case C", Fig. 1)

In "Cases A and B" the wall panel is exposed to a constant vertical load at every stage of the cycling excitation or horizontal deformation induced along the upper edge where the ballast is acting. In "Case C" the vertical load increases when the panel intends to uplift due to displacements along the upper horizontal edge. The advantage of the herein proposed testing procedures following the "Cases A and B" is avoiding the boundary conditions of the "Case C". The main problem of the protocol proposed by ASTM E72 is that it follows "Case C" due to the vertical constraining of the upper edge of the test specimen [GIRHAMMER ET AL. 2002]. In practice, "Case A" represents in general the behaviour of narrow elements and of elements loaded vertically only by flexible roof constructions. The "Case B" is typical for elements carrying floor constructions on top and "Case C" is the typical case of infill of a stiff surrounding frame.

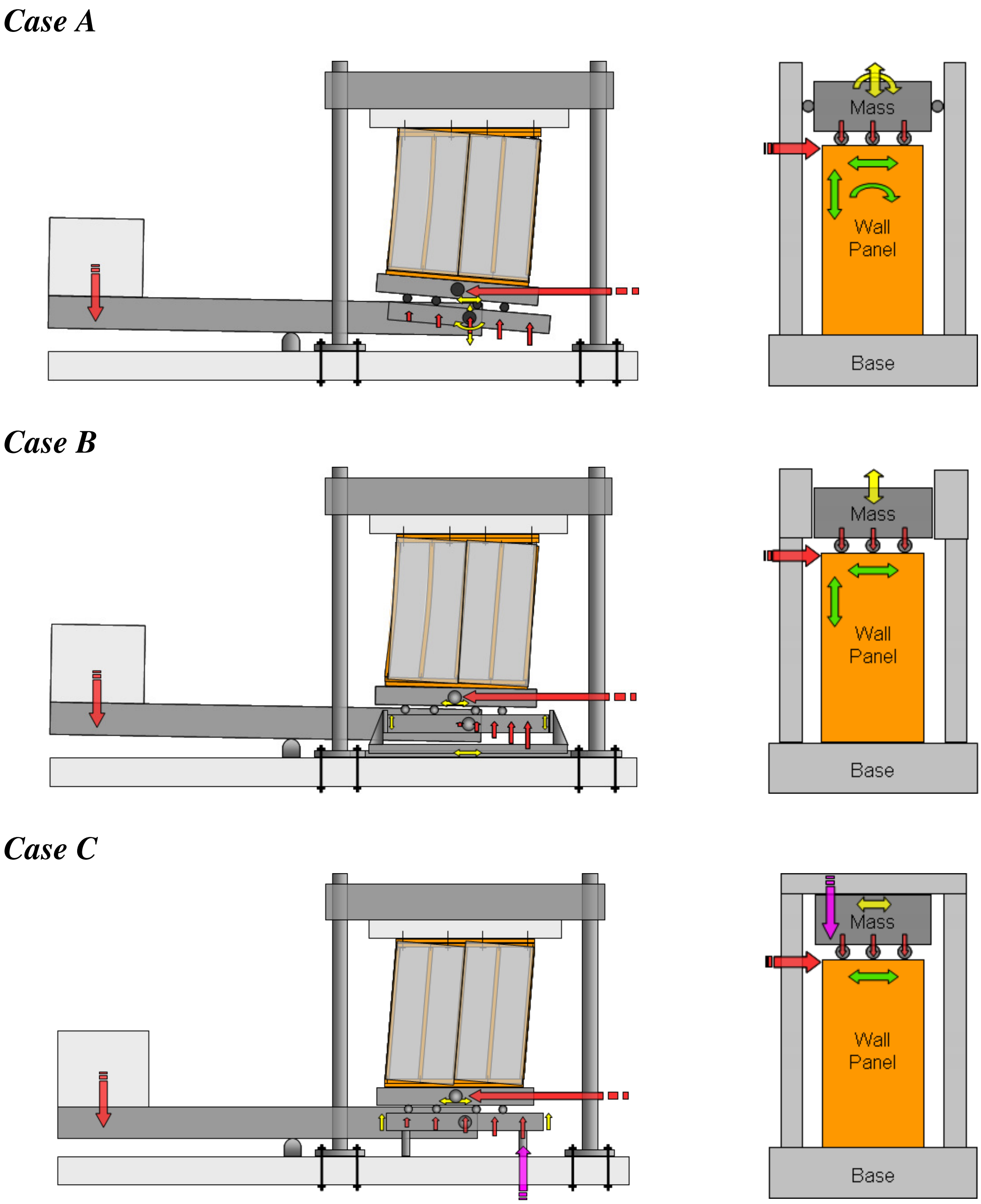


Figure 1: Three different boundary conditions of wall element tests which can be realised at UL FGG

2.2 Test setup at University of Ljubljana

Following the experiences obtained from testing of masonry elements, a universal shear wall test set-up was developed and installed at Faculty for Civil and Geodetic Engineering of University of Ljubljana in 1999 [DUJIC 2001]. The main idea of the new device was to use a gravity load induced by ballast as a constant vertical load and a displacement controlled hydraulic actuator driving the cyclic horizontal load. The main challenge was to simulate realistic boundary conditions that may occur during the action of an earthquake. In reality, the boundary conditions may change during an earthquake excitation because of changes of the building characteristics due to development of damages. Therefore, the testing device should allow the altering of boundary conditions from one to another test run.

The realised test set-up, shown in Fig. 2, enables testing of elements hereby simulating the three above described cases of boundary conditions. The horizontal load is applied by successively inducing displacements along the free edge of the specimen. The specimens (4) are turned upside-down and supported along the upper edge by a steel frame structure to ease application of gravity load by ballast. The test set-up is composed of six major parts, marked in Figure 2 by numbers 1 to 6. The pair of lever beams (1) follows the vertical deformation of the specimen, while constant vertical load induced by counterbalance acting on the specimen. The horizontal displacement is applied along the lower horizontal edge of the specimen by a single displacement-controlled actuator (5) that moves the roller beam (3). The beam rolls along the supporting beam (2) that is hinged between the pair of lever beams. During the testing, the lower edge of the panel is supported by a hinged (2) and horizontally movable mechanism (3), which allows its free horizontal movement and rotation (boundary condition of the “Case A”). Rotation of the supporting beam (2) can be constrained by both vertical side and horizontal sliding supports (6) allowing exclusively its vertical translation. The sliding supports enable the simulation of the boundary conditions of the “Case B”. Further alternation of the setup by blocking of the movement of the supporting beam in one direction (7) gives the boundary conditions of the “Case C”.

The set-up is calibrated for vertical and horizontal load. Strains measurements at the upper flanges of the lever beams in the cross-section above the lever support enable the control of the vertical load acting on the tested specimen. The horizontal action of the hydraulic actuator is controlled by a data acquisition and actuator control system by Röell/Amsler. The capacity of the test set up is 500kN of constant vertical load and 250kN of horizontal load in a displacement range of ± 200mm.

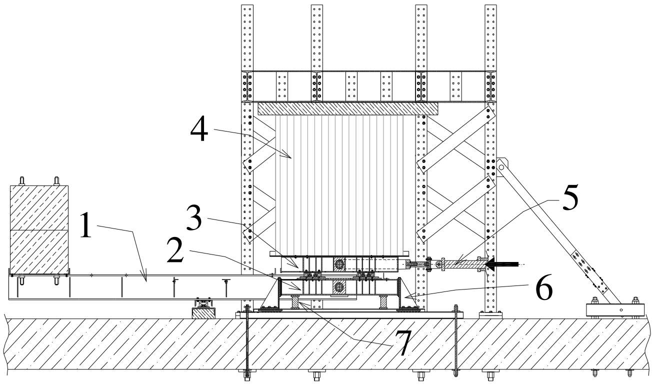


Figure 2: Longitudinal cross-section of set-up for testing of wall elements and test set-up in laboratory of FGG at University of Ljubljana.

3. TESTING PROCEDURES AND WALL ELEMENT RESPONSES

Well known critics of ASTM E 72 e.g. by [GRIFFITHS 1984] show the importance of proper boundary conditions to be used for realistic testing of wall elements. The European test standard EN 594 represents a step forward in the improvement of the test procedure. However, it does not solve the problem of taking into account the above described realistic boundary conditions in a proper way. EN 594 prescribes a partial anchoring of the elements along the bottom rail what does not conform to many systems that are presently on the market. Further, bottom rail anchoring is not an appropriate solution in earthquake prone areas where anchoring of the studs results in higher earthquake resistance the entire building. Besides this, EN 594 does not cover loadings that may occur in earthquake prone areas because it takes into account only a monotonous load protocol.

The main goal of this paper is to demonstrate the variety of testing possibilities using the herein proposed test approach with adaptable boundary conditions and different loading protocols from simple monotonous [EN 594, ASTM 564-95] to more complex cyclic ones. Cyclic testing can be carried out following the EN 12512:2001 or ISO 16670:2003 protocols or any other protocol - for example the CUREE protocol [KRAWINKLER 1999].

Two different types of wooden walls were tested: timber-framed walls with OSB or gypsum fibre board sheathing and solid cross-laminated wooden walls. The test protocol included in both cases boundary conditions of Cases A and B, three levels of vertical load and two patterns of horizontal load: monotonous according to EN 594 and cyclic according to ATC-1994.

It is evident, that the response of the shear walls depend primarily on the configuration and mechanical properties of the constituent elements and the assembly as a whole. However, ignoring the influence of different boundary conditions and the level of vertical load may lead to misinterpretation of the observed response. In Figure 3 three different patterns of wall behaviour are presented: shear, rocking and combined shear – rocking response. All of them can develop under boundary conditions of shear cantilever mechanism (“Case A”). The behaviour depends on the shear stiffness of the wall diaphragm as a whole, the magnitude of vertical load and the layout and mechanical characteristics of the anchors.

The shear response develops either if the panel is flexible in shear or if the magnitude of the vertical force is relatively high. The rocking response is typical for weakly anchored stiff elements or a low level of vertical loading. Combined behaviour can be observed, in most real cases a combined shear-rocking response occurs depending on different combinations of panel stiffness, anchoring and vertical load.

The response of the elements tested with “Case A” boundary conditions represents the conservative behaviour. If the same panel is exposed to other boundary conditions (“Case B” or “Case C”) the response values of rocking and combined shear-rocking may be higher than the values observed using “Case A” conditions. The reason therefore is the decrease of the tensile forces developed in the vertical edges of the element, consequently lowering the tensile loading of the anchors. Testing under conditions of the “Case B” is justified only when the behaviour of the element in the real building is governed by an in and out of plane stiff floor diaphragm (composite wood-concrete or solid wood slab). Testing under conditions of “Case C” is suitable for elements designed to act as frame infill, elements with glued-in-rods or for highly vertically loaded walls in the lowest storey of multi-storey buildings.

Published results of testing under conditions of the “Case C” can not be considered applicable to most realistic cases and may lead to serious mistakes if used in the design of structures. Due to underestimation of the importance of the boundary conditions the load bearing capacity of the elements is extremely overestimated especially when the elements are loaded with vertical loads of low intensity or when the elements are weakly anchored. However, at present the majority of known tests in Europe and hereon based expertise and technical approvals are based on the "Case C" conditions.

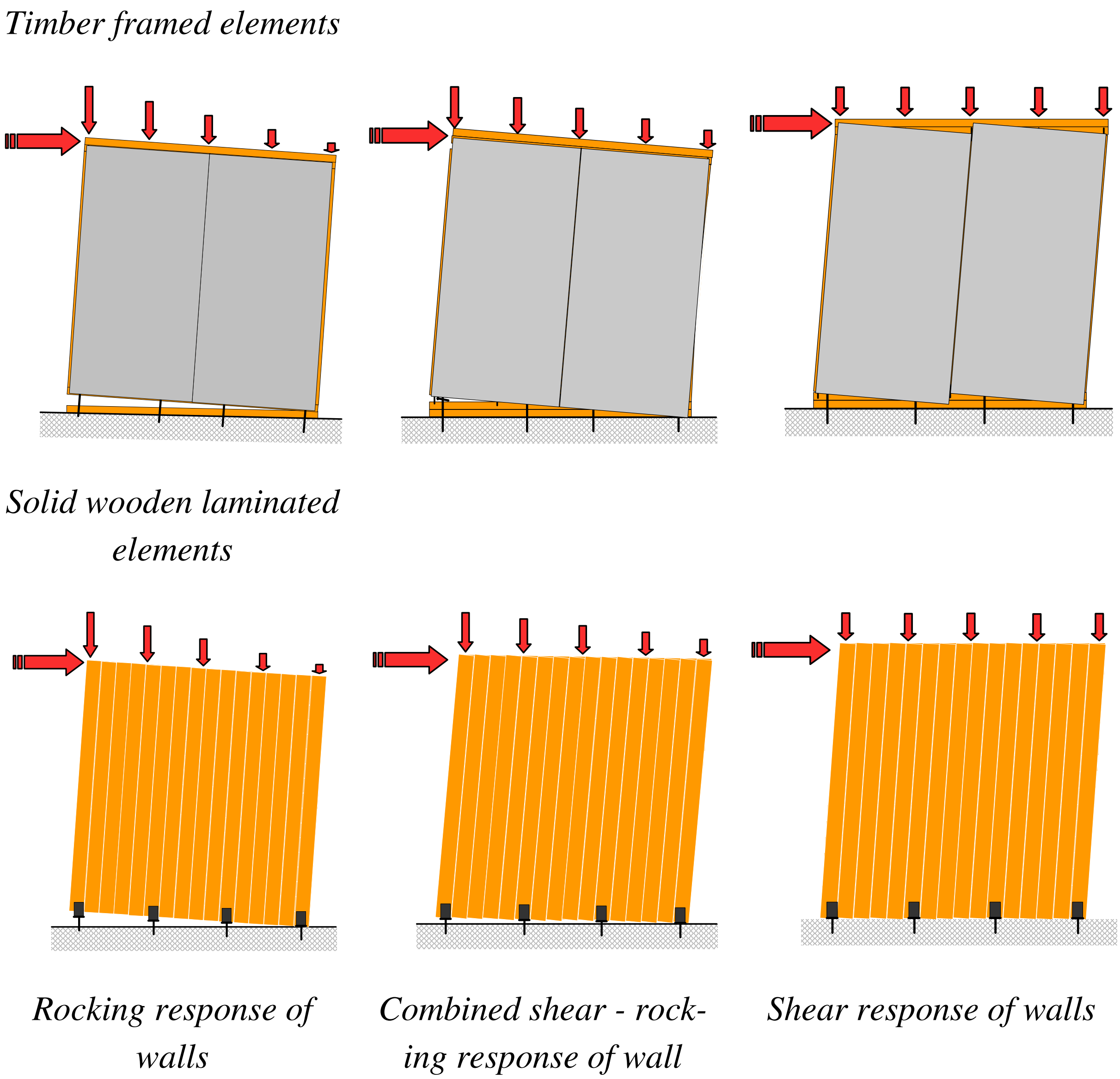


Figure 3: Typical responses of wooden wall elements exposed to combined vertical and horizontal load.

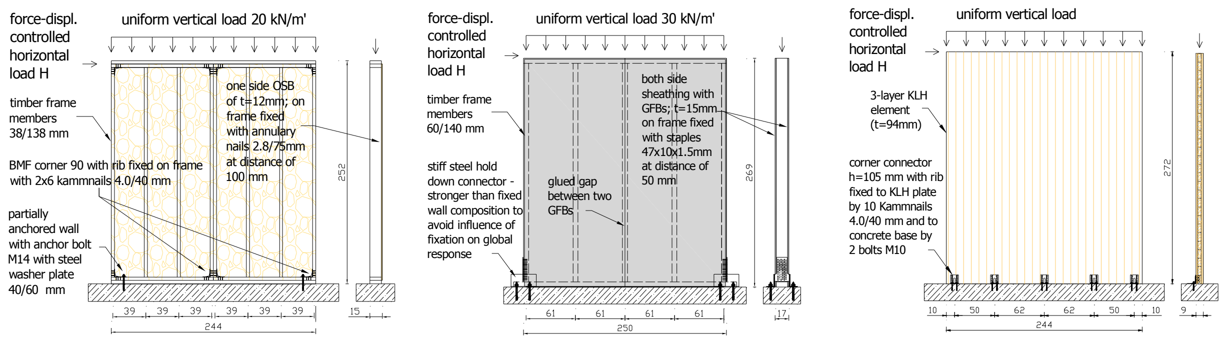
4. INFLUENCE OF LOADING PROTOCOL AND OF VERTICAL LOAD

The complete information about the mechanical characteristics of wooden wall elements and their anchoring can be obtained from responses both to monotonous and cyclic loading with proper combination of vertical forces (Figure 5a). The protocol of EN 594 is sufficiently covering the monotonous loading. The protocol of EN 12512 covers cyclic testing of particular joints made with mechanical fasteners, what is an insufficient tool for evaluation of the behaviour factor “q” needed for design of earthquake resistant buildings. The ISO 16670 standard also addresses exclusively the joints but the proposed protocol can be used for testing of wooden wall diaphragms, too. The reason therefore is that ultimate joint displacement is used, instead of yield slip (EN 12512) which is difficult to define. Since the ISO protocol is based on ultimate displacement it can forward a behaviour factor “q” as addressed in Eurocode 8. It is obvious that there is a need for development of an integral European standard covering both monotonous and cyclic testing of wall diaphragms.

The comparison of the responses of different wooden elements (Figure 4) subjected to cyclic and monotonous loading well illustrates the importance of cycling testing. In case of the element presented in Fig. 4a, the load carrying capacity of the element exposed to cyclic loading was about 15% lower than the resistance of the element exposed to monotonous loading. The cyclic response shows higher initial stiffness due to hardening of the fasteners exposed to low-cycle fatigue and lower ductility down to 50% of the ductility reached in monotonous loading. Therefore, earthquake design of wooden buildings can not be properly performed without data obtained from cyclic testing of elements exposed to different intensities of vertical load.

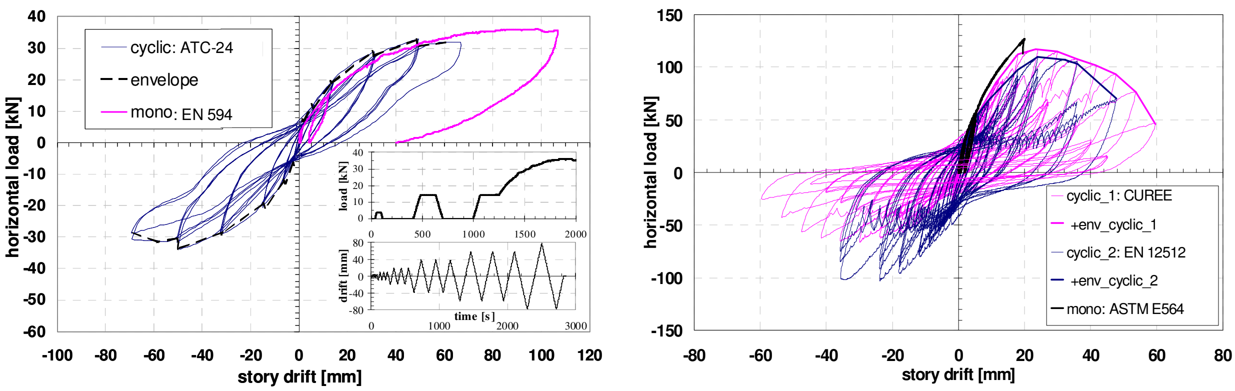
In general, wall elements mostly exhibit higher load-bearing capacity and ductility when exposed to monotonous loading in comparison when exposed to cyclic loading. Low-cycle fatigue of the mechanical fasteners in the wooden elements loaded in-plane by cyclic loading leads to a reduction of the element load-bearing capacity from 10 to 20% in comparison to one observed during monotonous testing. On the other side, the behaviour of fasteners exposed to cyclic loading can also result in a slightly higher stiffness of the elements than in case of monotonous loading.

Further, the behaviour of the wall elements is strongly influenced by the density of the fasteners along the sheathing-to- wooden frame contact and by the stiffness of the panel-to-foundation anchoring. When the fasteners are densely distributed and the anchoring is stiff, the cyclic response of the elements exhibits higher load-bearing capacity but ductility in comparison to the static response tends to decrease.



a) b) c)

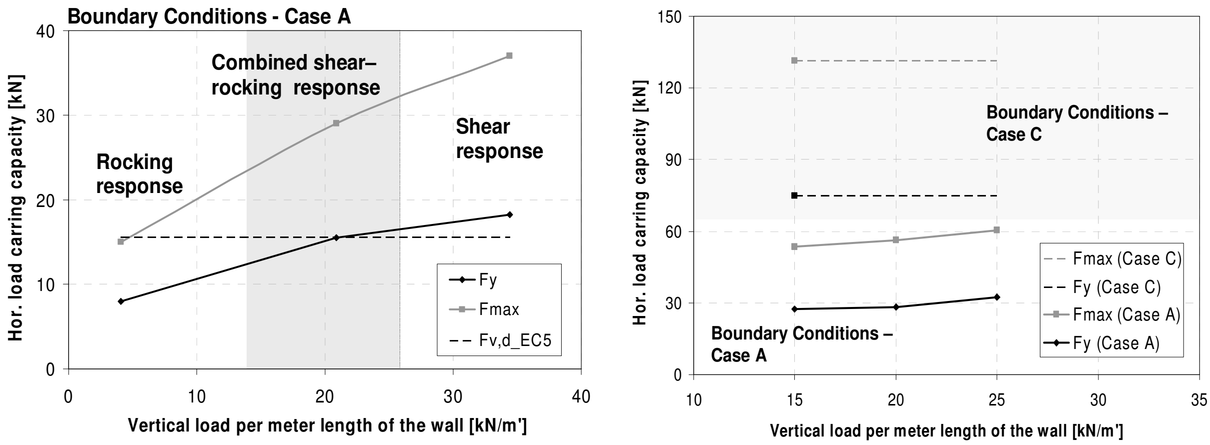
Figure 4: Configuration of one-side (a) and two-side (b) sheathed timber frame elements and solid wooden elements (c).



a) b)

Figure 5: Comparison of monotonic and cyclic response of different timber framed wall elements of length of 2.44 m, built up according to Figs. 4a and 4b and loaded vertically with 20 kN/m and 30 kN/m, respectively.

In the case of shear wall elements acc. to Fig. 4 b with sheathing boards of gypsum fiber board a dense distribution of fasteners and the specific properties of the board material lead to non-ductile failure during monotonous loading, while the same type of specimen behaves ductile during cycling loading (Fig. 5 b) without losing much of its load-bearing capacity and stiffness.



a) b)

Figure 6: Influence of vertical load intensity on load carrying capacity of wooden wall elements 2.44 m long.
a) Timber framed elements – configuration acc. to Fig. 4a
b) Solid wooden elements – configuration acc. to Fig. 4c

The graphs in Figure 5 reveal the influence of vertical load intensity both on the load carrying capacity and the type of response mechanisms. In the case of timber frame elements (Figure 4a) the rocking mechanism was observed at the lowest magnitude of vertical load and the shear mechanism at the highest magnitude of vertical load. The boundary conditions were of the “Case A” at all vertical load intensities. In the case of low vertical load, the anchorage system increases the racking resistance of the wall. Fully anchored framed wall elements having tie-downs at the leading stud have higher lateral resistance and load carrying capacity than partially anchored walls. At magnitudes of total vertical load above 50 kN (20 kN per meter length of the wall) the anchorage system did not significantly influence the lateral resistance of the shear wall anymore. In this case the shear mechanism was fully developed. Contrary, in case of the much stiffer solid wooden elements (Figure 4c) the shear mechanism did not develop in spite of changing the boundary conditions from “Case A” to “Case B”. The shear mechanism was finally obtained when the boundary conditions were set to the “Case C”.

5. CONCLUDING REMARKS

The importance of a proper taking into account of the boundary conditions and of the influence of vertical load and of the type of horizontal loading is evident from comparison of test results with different types of wooden shear wall elements. The clear differences between monotonic and cyclic response, strongly influenced by the type of element build-up reveal the need for further development of standard protocols for wooden wall diaphragms used for structures located in earthquake prone areas. The type of sheeting material is very important in this context. New standards should implement the concept of performance based earthquake engineering design to obtain experimental data needed for evaluation of the behaviour factor "q".

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